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| Title: | "What is it?" Inertial Confinement Fusion |
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# “What is it?” Inertial Confinement Fusion

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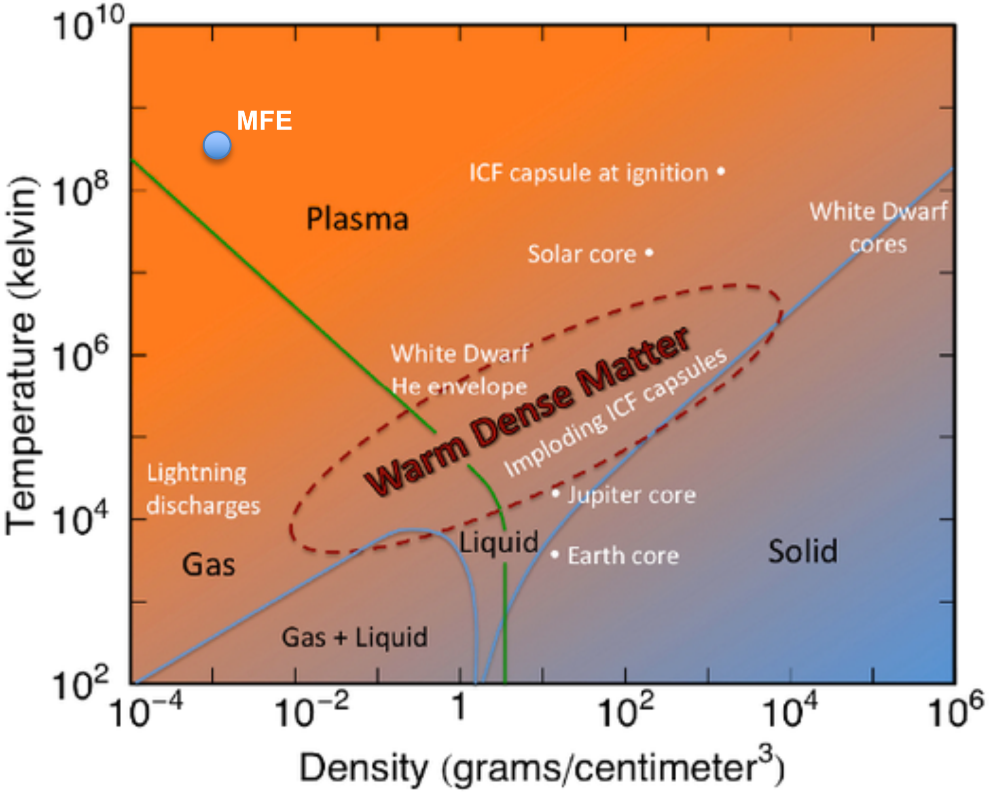
December 2, 2019

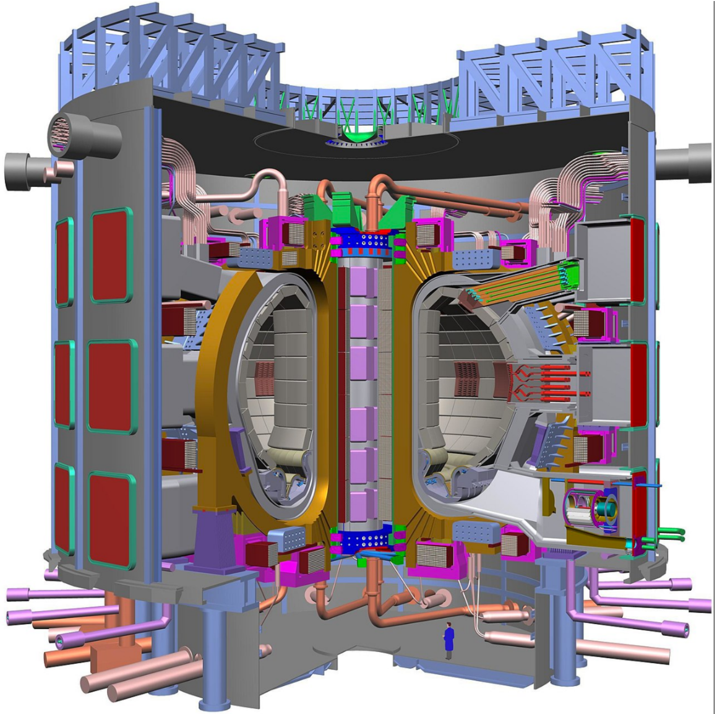
# Outline

- Magnetic and Inertial fusion energy – definition
- Basics of Inertial confinement fusion + ignition
- Current ignition status
- Ignition/HED component physics
- Facilities
- Next Steps
- Conclusions

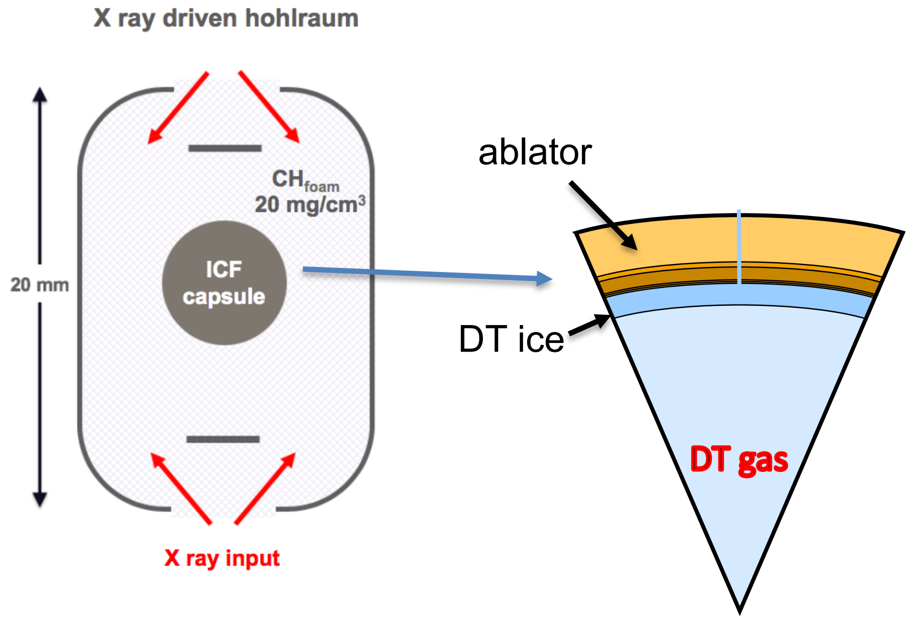
# Plasma Physics cover most of ρ,T space



# There are two main concepts for fusion energy



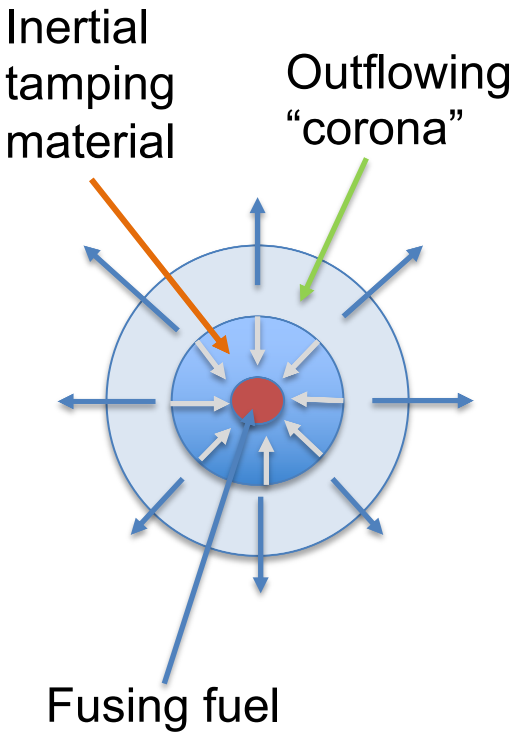
Magnetic Confinement




Inertial Confinement

# Definition of ICF

- Inertial Confinement Fusion (ICF) uses the inertia of the ablator and/or fuel mass to confine a plasma long enough for fusion to occur.
- ICF uses energy to ablate material from the outside of a capsule. The rocket effect implodes the fuel

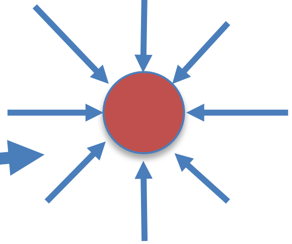


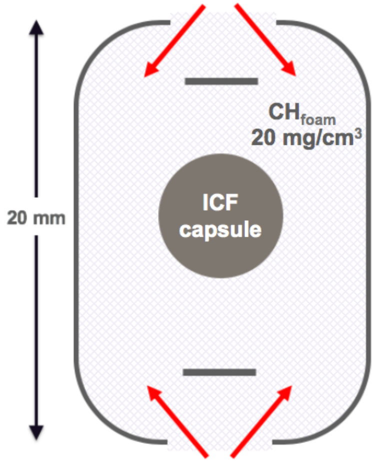
# Why do we care about ICF?

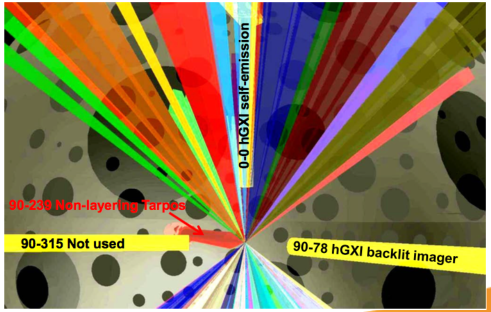
1. First, ICF is a subset of high energy density (HED) physics -- this is what happens when you dump at least 1 kJ of energy into $\leq$1mm$^3$ or less
2. HED physics occurs in astrophysics, weapons, and facilities such as OMEGA, Z machine, and the NIF
3. Plasma effects can be important here. Although fluid-like phenomena occur, are they the same as for normal fluid mechanics?
4. ICF could lead to Inertial Fusion Energy
5. HED/ICF can create conditions more extreme than any other lab
6. Robust TN burn can create EMP – needed to understand the response of electronics (power grid) to insults from CME
7. Once robust TN burn is achieved, we can "step down" to understand ignition failures and verify ignition scaling laws

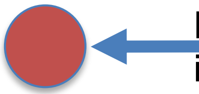
# "Flavors" of ICF

- Indirect Drive
- Direct Drive
- "Polar Direct Drive"
- Fast Ignition
- others



# Flavors of ignition design

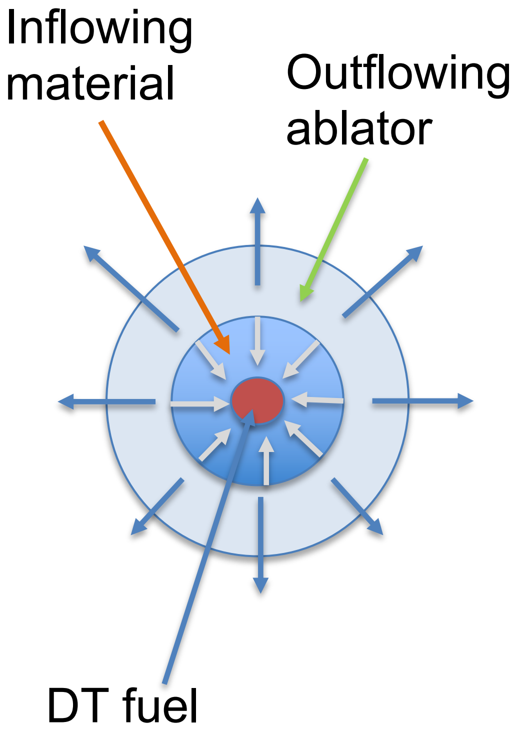
- Indirect Drive (ID)
  - Uses a hohlraum to lessen laser drive non-uniformity and hydro instabilities
  - Has time-dependent asymmetry and reduces capsule absorbed energy
  - Laser-plasma instability (LPI) is a big issue (near vacuum hohlraum, short pulse)
  - Current effort at LLNL uses this
- Direct Drive (DD)
  - Tends to provide more uniform illumination – less low-mode asymmetry
  - Sensitive to laser “speckle” patterns and beam overlap
  - LPI also an issue

# Flavors of ignition design (cont'd)

- Polar Direct Drive (PDD)
  - This uses the current illumination pattern on the NIF for direct drive
  - One can adjust the beam pointings and intensity to obtain a uniform drive
  - Has not been used for ignition capsules yet
- Multi-shell designs
  - Can be done with ID (double shell), DD, or PDD (Revolver)
  - Use velocity multiplication from shell collisions for symmetry and simple drive
  - Sensitive to presence of joints, fill tubes and implosion symmetry
- Fast Ignition
  - Semi-compress a capsule to less than ignition density and temperature
  - Use an electron or charge particle beam to provide a "spark" for ignition
  - Concern on how to get beam energy to capsule center without perturbing fuel too much

# Basic principle of ICF

1. Energy from a driver impinges rapidly on the ablator, which heats up and expands
2. Part of the ablator expands outward, the rest of the ablator and fuel implodes ($V_{imp} \geq 300$ km/s)
3. As the DT fuel compresses, it heats up and above 6 keV, it can ignite and burn
4. The hot DT will burn the hot (and cold) fuel, producing yield. Inertia from the imploding ablator holds the capsule together briefly (<1 ns)
5. The liberated energy causes the tamping material to expand, and DT burn ceases



# How do we get a plasma to ignite?

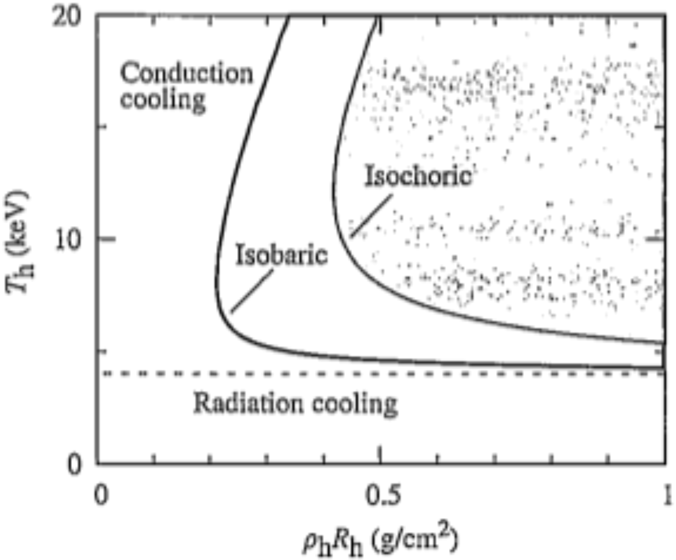
- Various simple estimates[1,2,3] suggest scaling of kinetic energy required for ignition scales as:
- $E_{ign} \sim \alpha^{1.7} V_{imp}^{-5.5}$ to $E_{ign} \sim \alpha^{3.0} V_{imp}^{-10.0}$
- Where $\alpha$ is the fuel adiabat and $V_{imp}$ is the implosion velocity
- We want less energy to ignite, so higher velocity and lower adiabat are crucial!
- This assumes a 1-D spherical implosion, no mix and adequate DT fuel mass

# How do we get a plasma to ignite? (cont'd)

- Energy Balance says rate of energy change in the DT fuel is
- $\frac{dE}{dt} = W_{fus} - P\frac{dV}{dt} - W_{cond} - W_{Brem} - W_{rad}$

Where $W_{fus}$ is fusion power deposition, $W_{cond}$ is energy loss from thermal conduction, $W_{brem}$ is bremsstrahlung loss, and $W_{rad}$ is blackbody radiation loss

- $W_{fus}$ is adequately described by $\alpha$ particle deposition
- $P\frac{dV}{dt}$ is mechanical energy loss ($3G\rho_h T_h v/R_h$) (sphere)
- $W_{cond}$ is energy loss from electron conduction
- $W_{brem}$ dominates radiation loss at a few keV ($A_b\rho_h T_h^{1/2}$)
- $W_{rad}$ is blackbody radiation loss (relevant only at high temps)
- Ignition requires $\frac{dE}{dt}$ to be large (next slide)

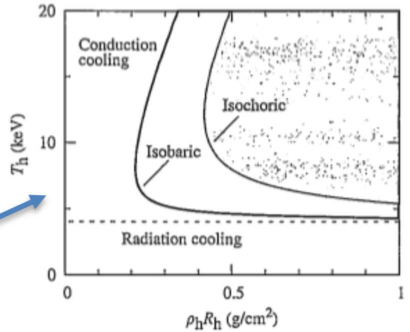


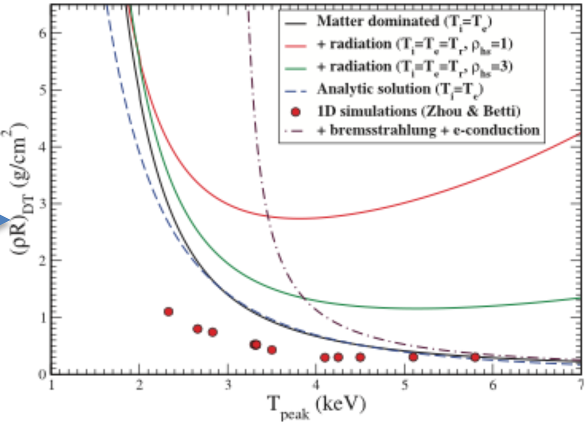

Conduction prevents ignition for $\rho R<0.3$ g/cm$^2$
Bremsstrahlung prevents ignition below 4 keV

"Isobaric" is "hot spot" ignition, while "Isochoric" is volume ignition

# How do we get a plasma to ignite? (cont'd)

- To determine the boundary for ignition, we set $\frac{dE}{dt} = 0$, so
- $W_{fus} = P\,\frac{dV}{dt} - W_{cond} - W_{brem}$ OR
- $(A_\alpha\langle\sigma v\rangle f_\alpha - A_b T^{1/2})(\rho R)^2 - A_m T^{3/2}(\rho R) - A_{cond} T^{7/2} > 0$
- In the isobaric limit, $A_m$ (or $P\,\frac{dV}{dt}$) is 0, so
- $\rho R = \{ [A_{cond} T^{7/2}]/[A_\alpha\langle\sigma v\rangle f_\alpha - A_b T^{1/2}] \}^{1/2}$
- A more modern effort leads to the figure on the right
- All of this relates to hot spot ignition
- Volume ignition requires igniting the entire fuel

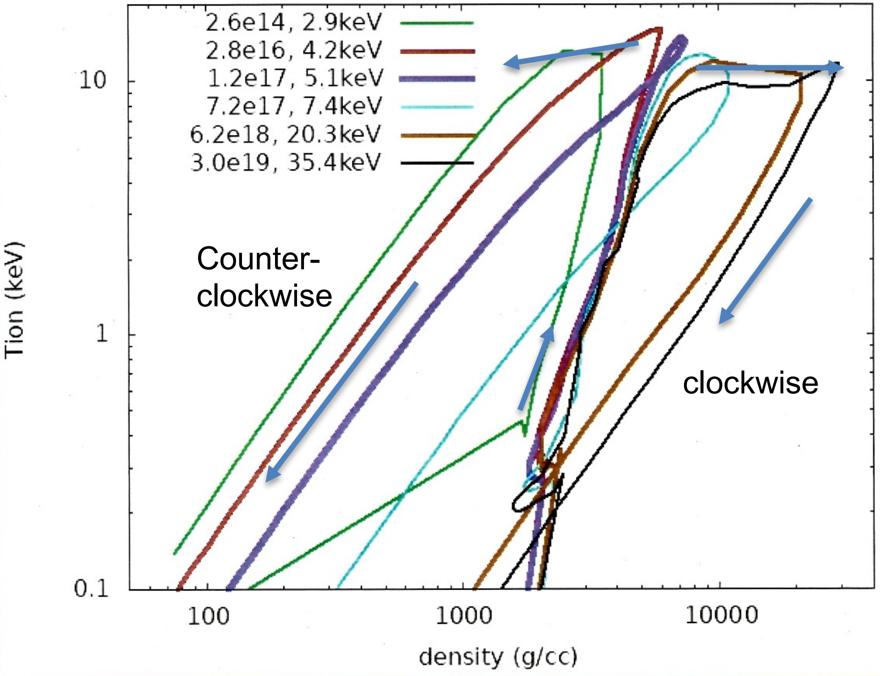


# When do we know the capsule ignited?

- The definition of ignition is not universally agreed upon
- NAS has declared it to be ~1 MJ for the NIF
- Ignition has several features, among them being a jump in the burn averaged Tion around 6 keV and a hot spot $\rho R > 0.3$ g/cm$^2$

- A plot of central density versus temperature shows an interesting trend with yield
- Below the ignition threshold (~1 MJ = $4 \times 10^{17}$ n), the trend is counter-clockwise
- Above this threshold, the trend is clockwise
- In this plot, the run with a yield of $1.2 \times 10^{17}$ n's is at the transition point



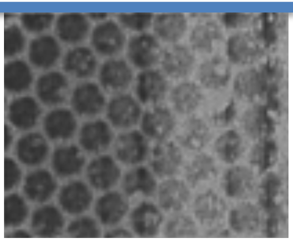
# Obstacles to ignition

- Capsule imperfections
  - Surface finish
  - Fill tube or mounting stalk
  - Glue spot
  - Joints
- Richtmyer-Meshkov instability with shock passage through interface
- Preheat from hot electrons or high energy x-rays
- Rayleigh-Taylor instabilities upon deceleration or explosion
- Asymmetric implosions (drive or shell collision) – exacerbated by high convergence
- Turbulent mix (we suspect rarely encountered)

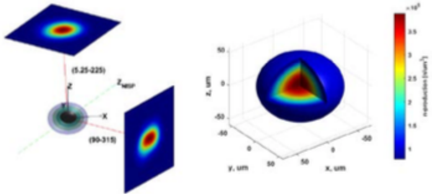
# Many diagnostics are used in HED/ICF

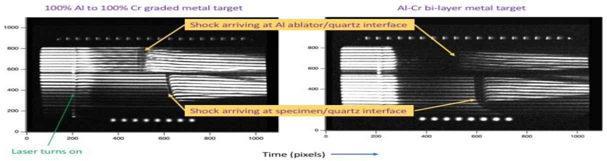
- X-ray framing cameras – images with resolutions of 10 $\mu$m or less
- X-ray spectra – streak spectra (time), time integrated, and MMI (time+space)
- Hot electron diagnostics – look for preheat
- Neutron imaging (DT and scattered images)
- Neutron time of flight (time dependent neutron emission and neutron spectra)
- Gamma-ray history
- DANTE – series of x-ray diodes to obtain drive temperature in hohlraum
- VISAR – obtain time dependent velocity of an interface
- And many others….

MMI

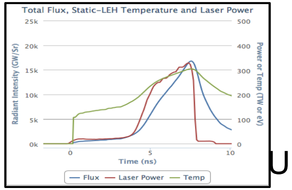


Neutron image



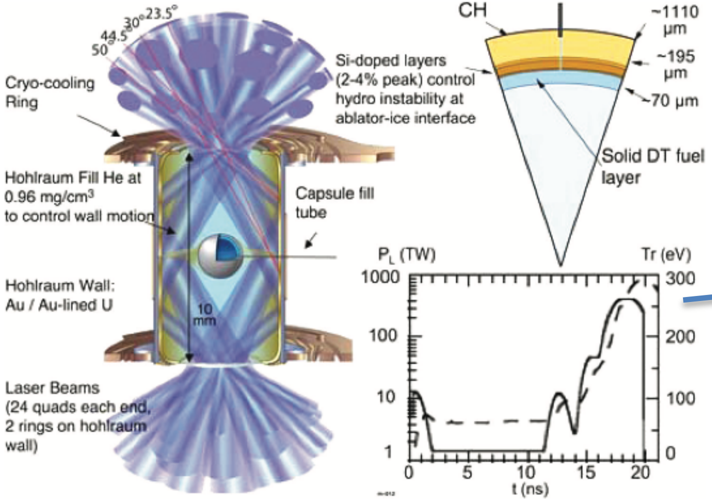


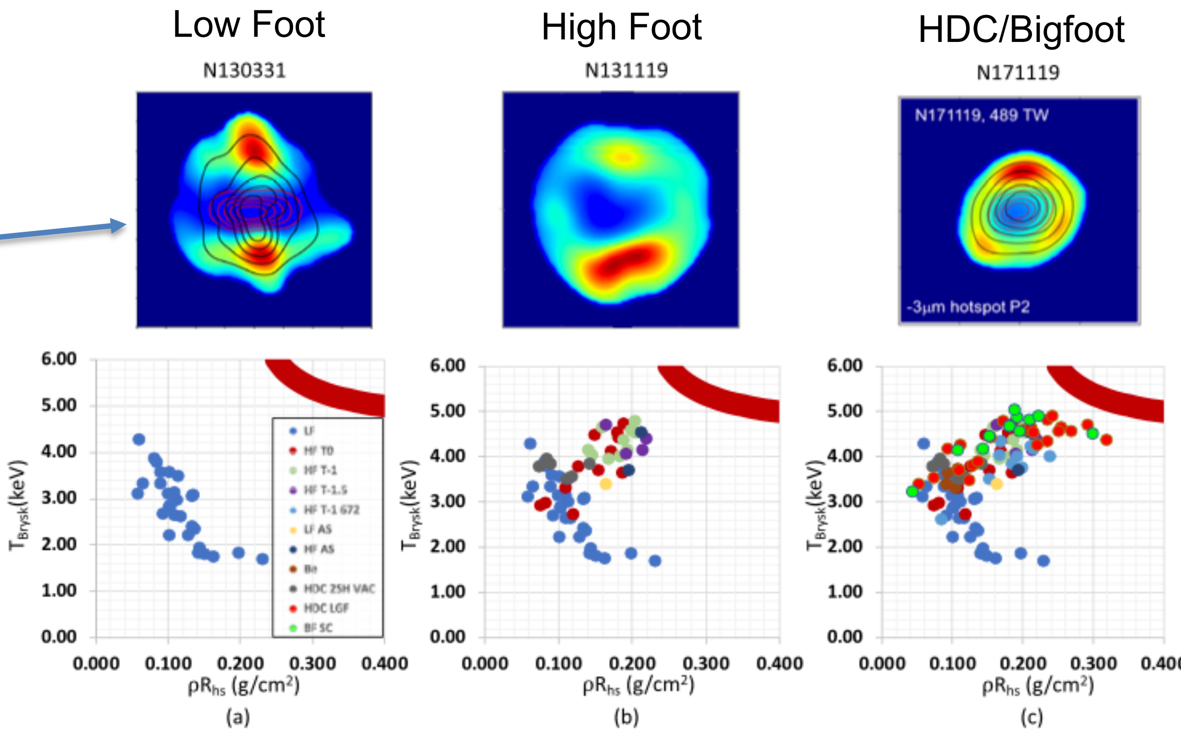

VISAR




DANTE

# NIF progress towards ignition



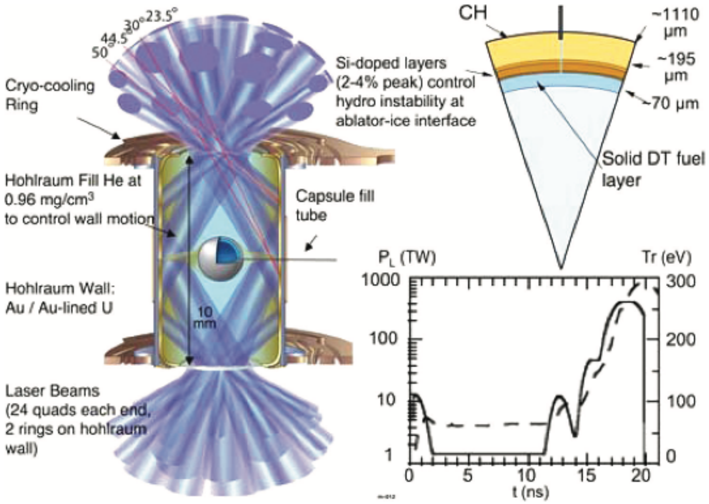



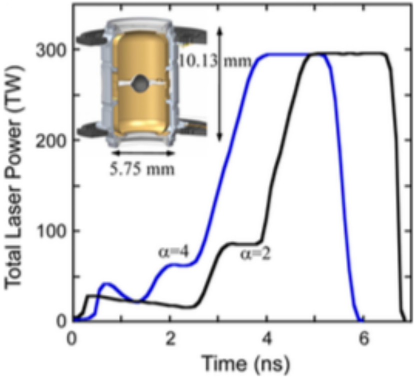

Changes

- Move to near-vacuum hohlraum
- Simpler laser pulse
- Lower convergence ratio
- Increase implosion velocity

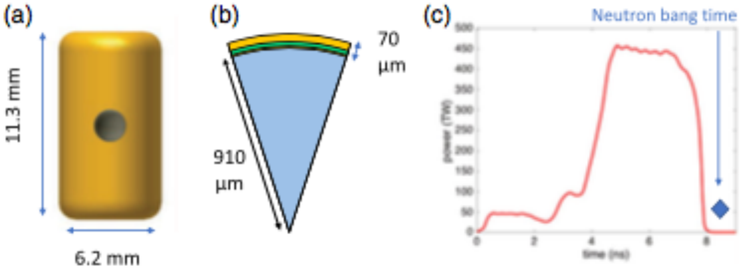
O. Hurricane, et al., PoP, **26**, 052704 (2019)

# Record performance is about 56 kJ




HDC ($\alpha$=2) and Bigfoot ($\alpha$=4) laser pulses and hohlraum
Max yield ~$1.95 \times 10^{16}$




Hohlraum, capsule, And laser pulse for Best HDC capsule
$1.9 \times 10^{16}$

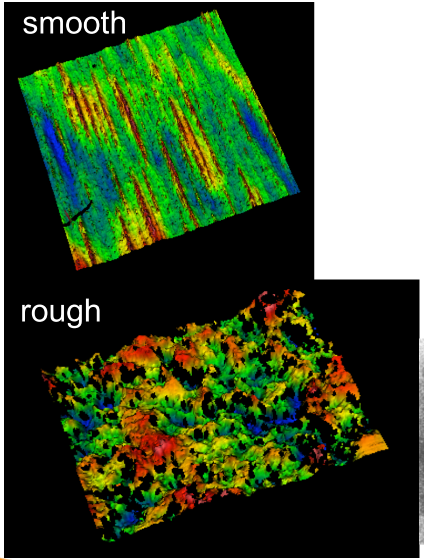
NIC hohlraum, capsule, laser pulse
Adiabat supposed to be ~1.6 (2.8)
Best yield <$10^{15}$

# Some HED component physics of ignition

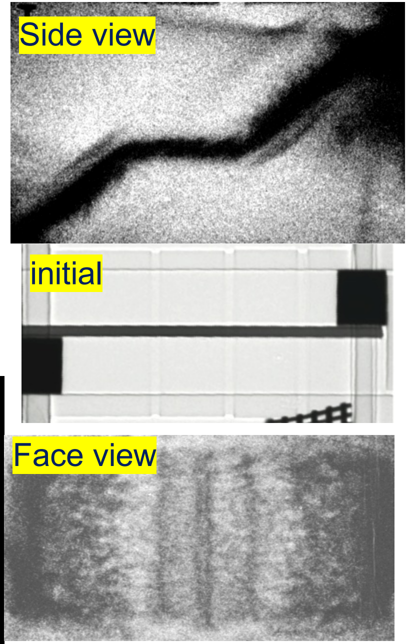
- Shock/shear experiments look at K-H instability
- CylDRT looks at R-T instability in cylindrical convergence
- Marble looks at chuck/atomic mix
- Separated reactant capsules examine mix depth
- Mshock and reshock examine multiple shocks hitting an interface
- Various experiments were affected by preheat
- Surface finish, fill tubes and glue spots affect capsule implosions in particular

# Shock/Shear show K-H driven mix width growth

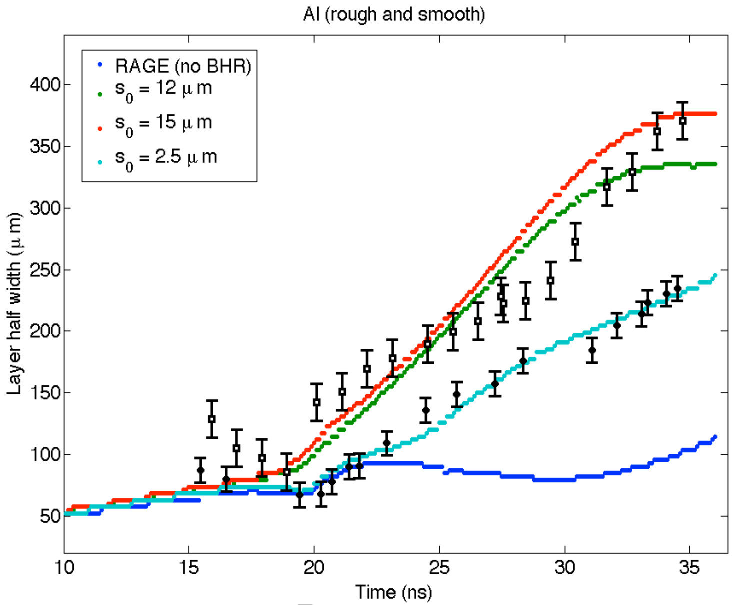
Surface scans




radiographs



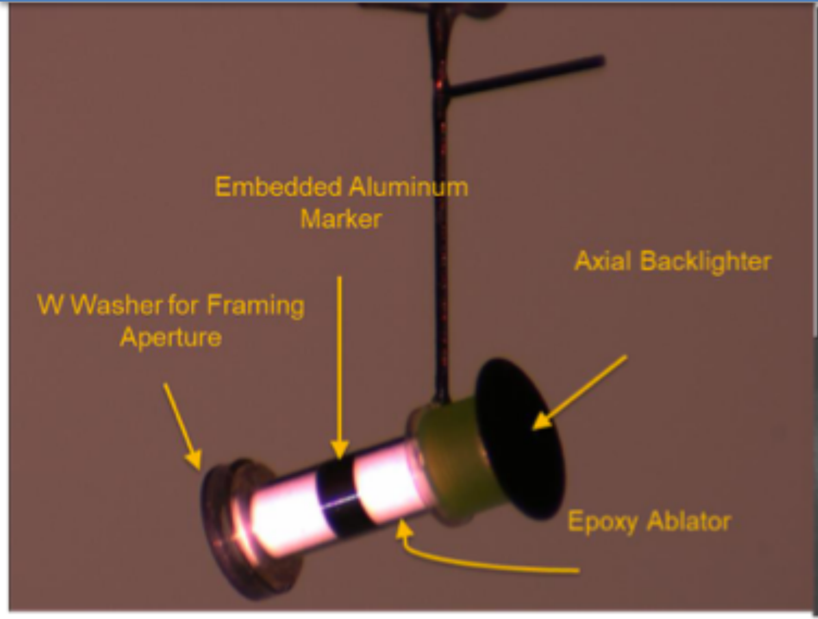

We use Simulations With a turbulent mix model to replicate data

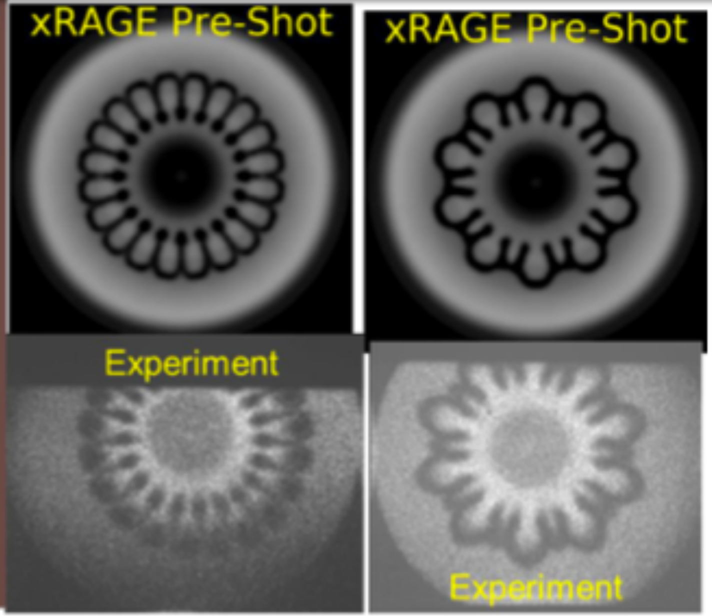


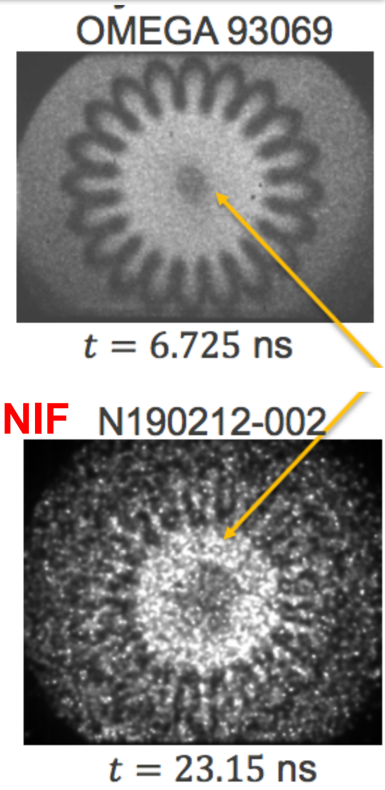

Data plots

Phys. Plasmas, 22, 056303 (2015)
Phys. Plasmas, 25, 056315 (2018)

# CylDRT shows beautiful bubble/spike evolution

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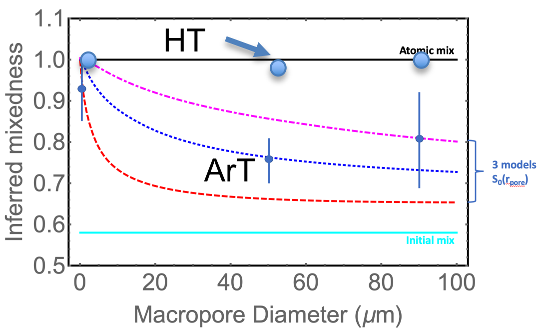
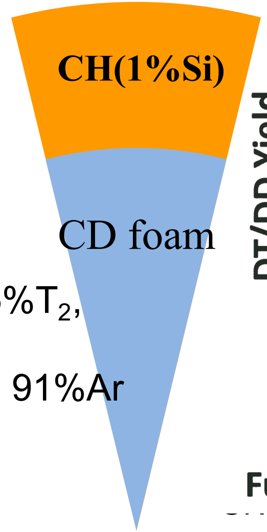
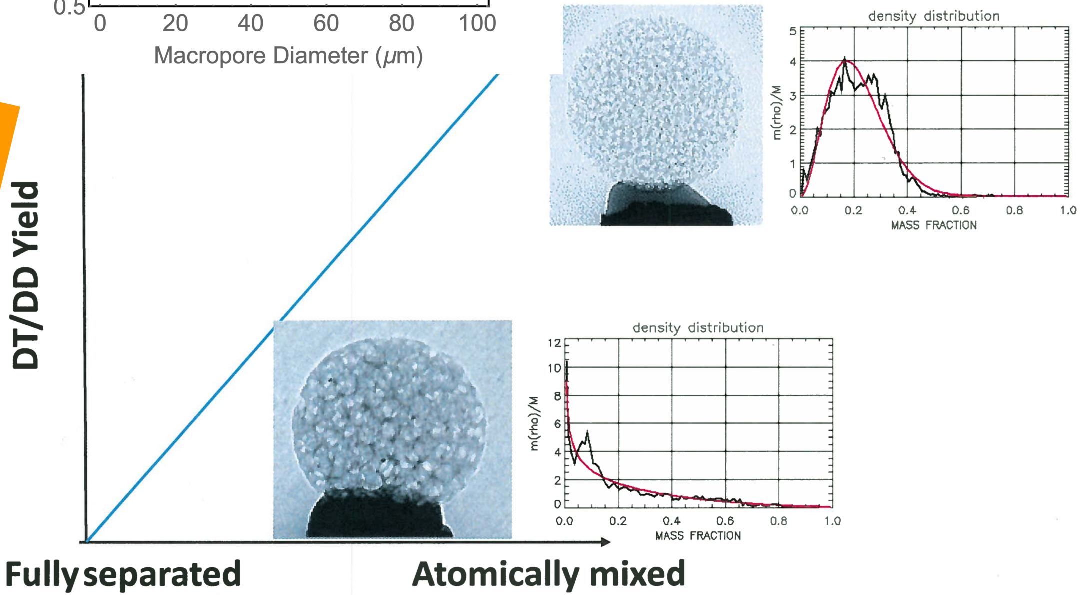
# Marble experiments show chunk/atomic mix

- During the implosion, the D in the foam and the T in the gas mix produce DT neutrons. The more mix, the more DT neutrons; DD neutrons are nearly insensitive to mix.




Gas fill 5%$T_2$, 95% $H_2$
or 9%$T_2$, 91%Ar

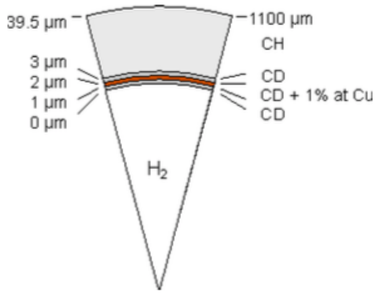


# Separated reactant capsules show mix depth <1μm

- There are numerous studies with DT reactions and/or spectroscopic dopants to diagnose mix depth
- Below, we show a spectroscopic example. Other capsules show mix depths of <0.5 μm

Phys. Plasmas, 21, 063306 (2014)

xRage does a nice job of matching the data. xRage shows no lines for n130618




Pie diagram for N130618. The Cu dopant is buried 1 μm deep. Shot N130617 has the dopant next to the gas

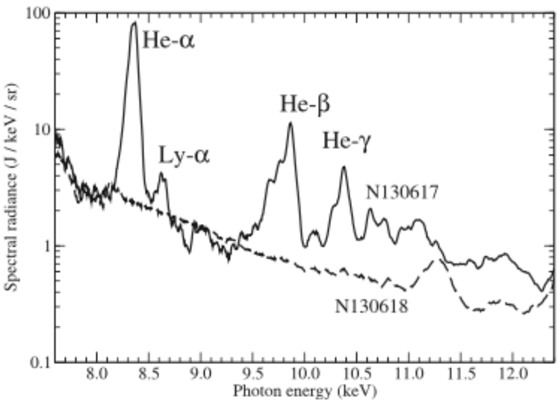
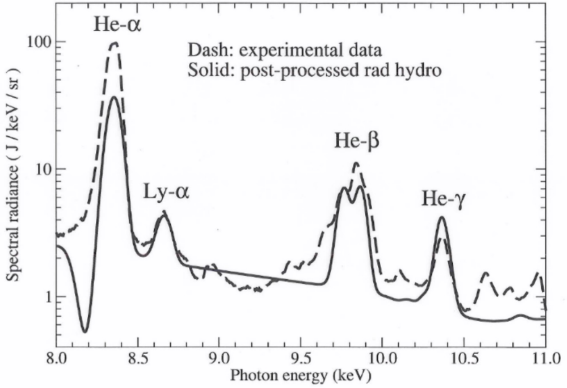
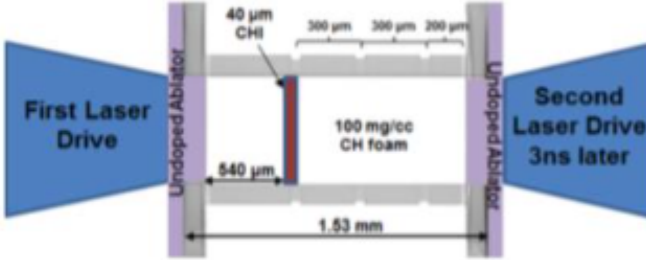



FIG. 2. Experimental x-ray spectra for shots N130617 and N130618 (Cu dopant).



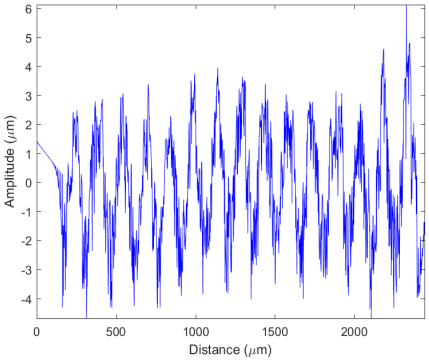
# Mshock and reshock show transition to turbulence

Mshock stands for “multiple shocks, which Examines the behavior of a machined foil To shock and reshock behavior.

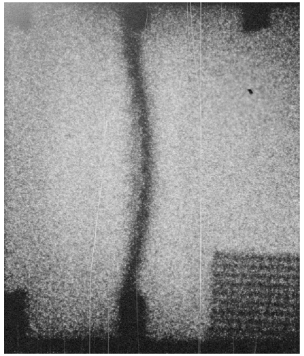



‘Nominal configuration’

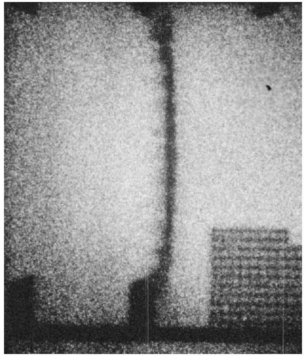
Initial mode structure



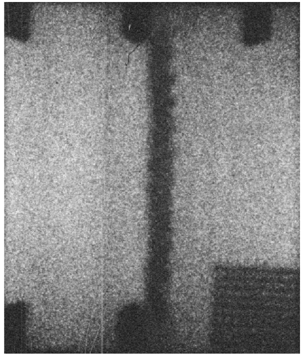

Post-shock



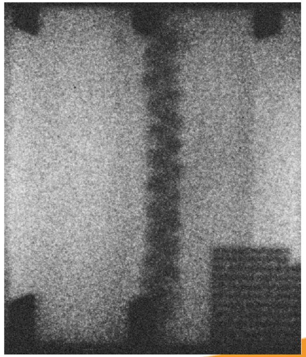
Post-shock



Post-reshock



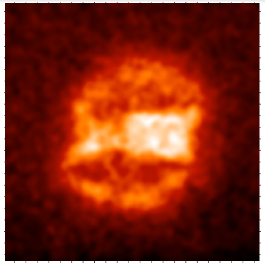
Post-reshock



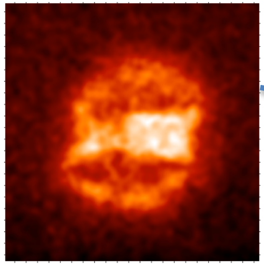
# X-ray preheat can affect data and implosions

- Preheat is a term to indicate unwanted heating of a target in advance of the main shock
- In ID, this comes from high energy x-rays from the gold wall
- In this case, preheat comes from hot electrons, which affects the implosion symmetry

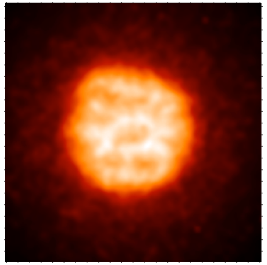
N121207-001
$E_L$ = 607 kJ
$E_p/E_e$ = 0.771
$I=1.9\times10^{15}$W/cm$^2$

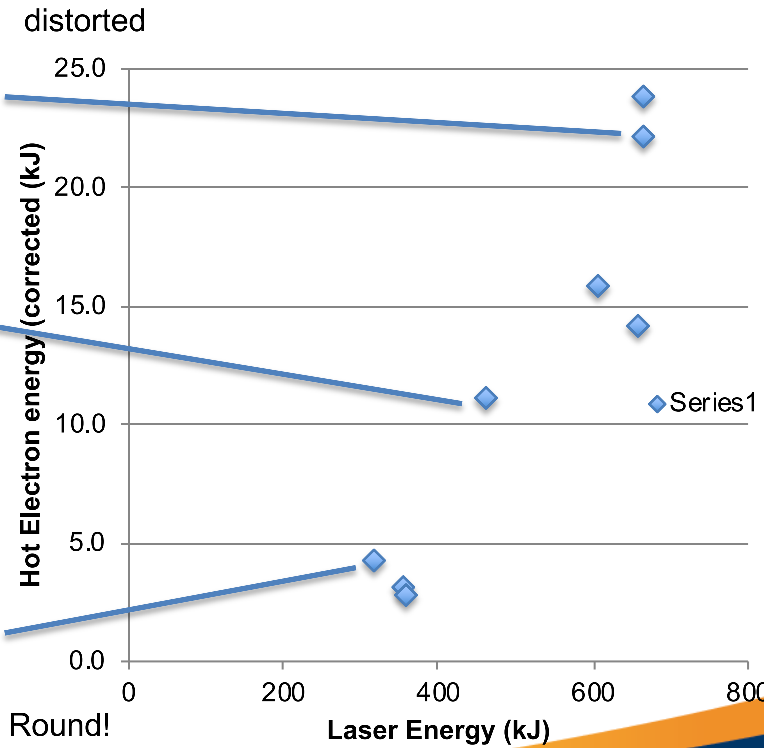


N130321-001
$E_L$ = 462 kJ
$E_p/E_e$ = 0.842
$I=1.4\times10^{15}$W/cm$^2$



N130320-001
$E_L$ = 319 kJ
$E_p/E_e$ = 0.833
$I=1.0\times10^{15}$W/cm$^2$





# Capsule imperfections can degrade implosions

- Capsules and other experiments are 3-D in real life
- Computing power has finally gotten to where 3-D simulations are possible
- Besides pretty pictures, they show the limits of 2-D simulations
- Not shown here are results of 2-D and 3-D simulations with surface roughness and all the features
- These replicate performance results without the need for turbulent mix models!

Phys. Plasmas, 26, 012707; Phys. Plasmas, 26, 050601 (2019)

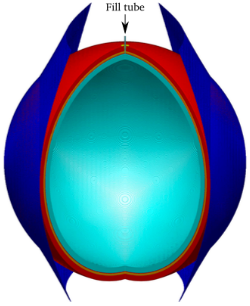



**FIG. 6.** Initial conditions for the 3D simulation with a quadrant cut out to aid in visualization. Blue: support tent, red: HDC ablator layers, orange: W-doped HDC ablator layer (for the simulation of the full scale design only), yellow: glue spot, turquoise: wetted foam layer, and grey: glass (fill tube).

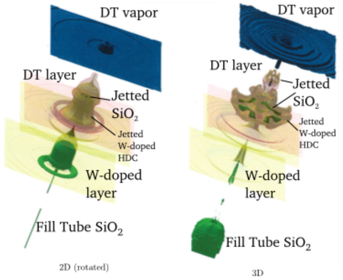
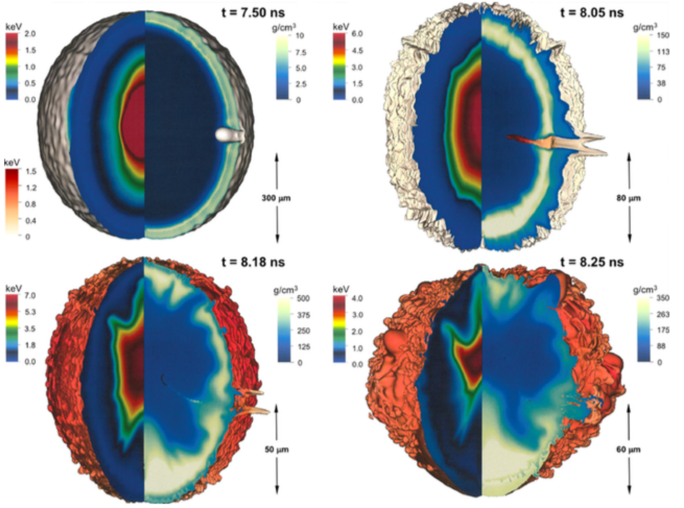
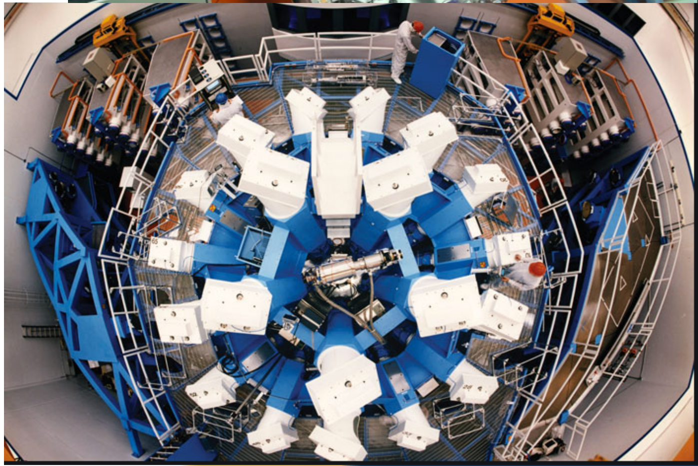



**FIG. 12.** Comparison of material distribution in the fill tube jet at $t = 5.7$ ns for 2D (synthetically rotated) and 3D simulations of the full scale wetted foam design from Ref. 5.



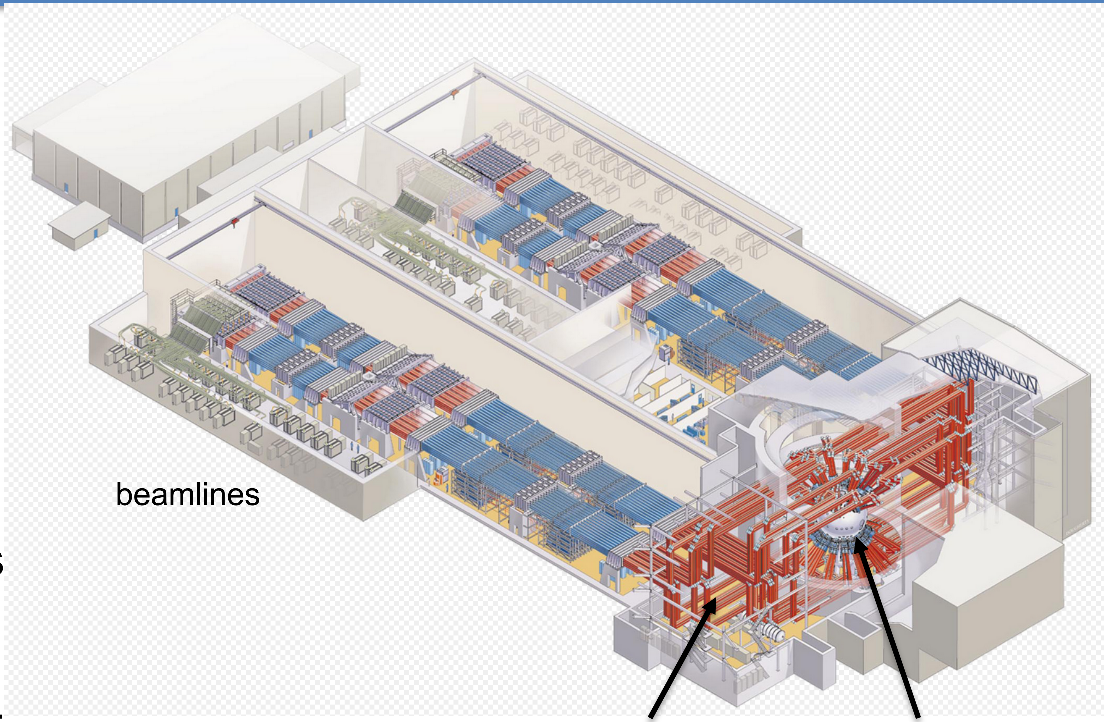
# Facilities: OMEGA laser at LLE

- Located at University of Rochester
- Has 60 beams for the main laser and add-on OMEGA-EP
- Maximum energy is about 30 kJ ($3\omega$)
- Capable of 10 to 15 shots per day
- Used for
  - ➢ Investigating HED Physics
  - ➢ Doing “proof of principle” experiments for the NIF
  - ➢ Direct drive implosions
- Very capable, but much less energy than the NIF



# Facilities: National Ignition Facility

- Located at LLNL
- Has 192 beams arranged for indirect drive
- Maximum energy is ~2 MJ ($3\omega$) and power is 500 TW
- Capable of 1 to 3 shots per day
- Used for
  - Investigating HED Physics
  - Ignition attempts
  - Stewardship science/weapons effects experiments
- Current record yield is $1.9 \times 10^{16}$ DT neutrons (~56 kJ)




Target chamber was in "Star Trek: Into Darkness"

# What next?

- Consensus is ignition is unlikely at NIF, even with modest upgrades
- That said, LLNL is suggesting a “mid-life” upgrade to 2.6 MJ (3$\omega$) and 600 TW
- In the meantime, it is a 2 MJ laser that can do really great HED science!

- LANL is pushing an approach (LLNL and SNL also involved) to look at a “next generation” facility
- Goal would be 2 to 5 MJ absorbed by a capsule with an energy output of 100+ MJ
- Would enable a whole new class of HED experiments

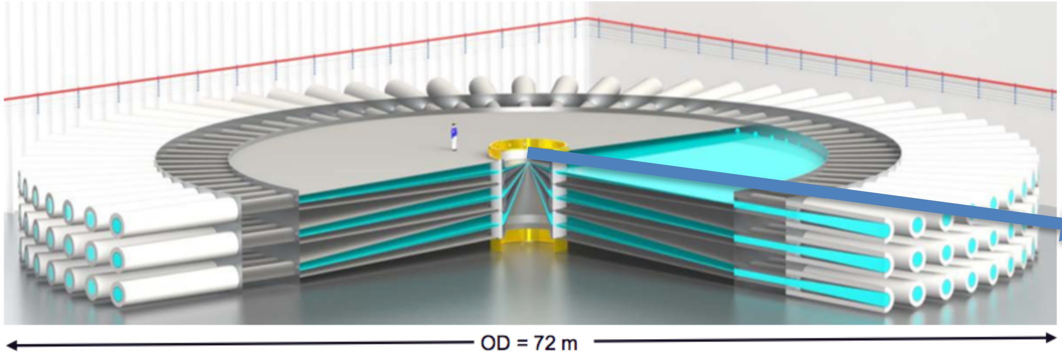
# Pulsed power is current suggestion for next generation driver*

Olson, et al., Fusion Technology, **35**, 260 (1999)

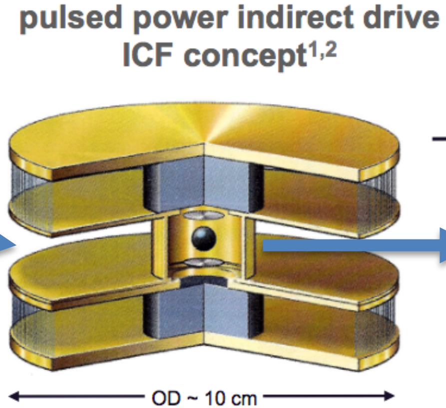
Large 100 MJ, 1000 TW Linear Transformer Driver Pulsed power machine

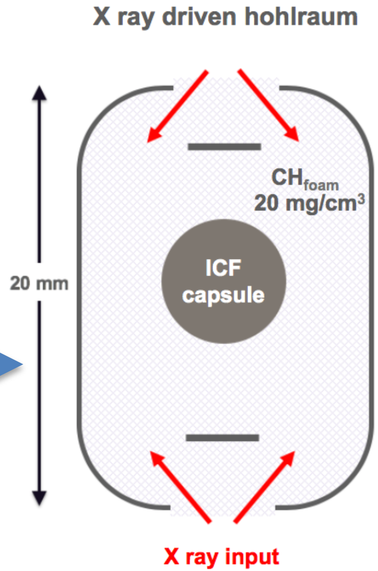
*Stygar et al., Phys. Rev. STAB, **18**, 110401 (2015)

Drives two x-ray pinches on either side of a hohlraum




10 MJ, 1000 TW pulsed power concept design



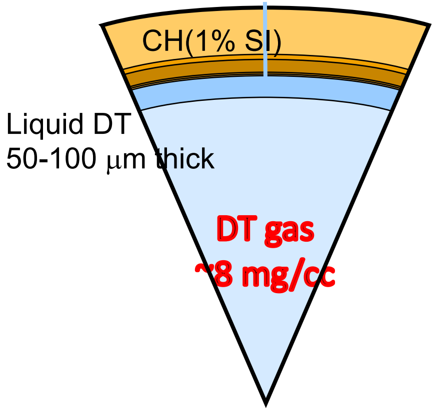




Sanford et al., Phys. Rev. Lett, **83**, 5511 (1999)

# LANL is leading groundwork experiments

- Key question: what is minimum hohlraum radius needed for symmetric implosion of an x-ray driven capsule?
- If the ratio is ~2.7, then driver energy is about 4x capsule absorbed energy (ratio is 4, then driver is 10x)
- Currently working to conduct relevant experiments at OMEGA, Z-machine and the NIF
- Even if everything works out, such a facility would not be built until after 2030

Possible NextGen capsule
OR ~ 2500 μm
Abl thick 500 μm
2 to 5 MJ absorbed energy




Disclaimer: these are my opinions, not an official position!

# ICF/HED is a vital area of plasma physics

- The plasma world is pervasive and impacts our everyday life
- However, much of the modeling is done by rad-hydro (fluid) codes
- How accurate is that? We need to know
- The physics impacts stockpile stewardship

- HED has a wealth of diagnostics and we have the ability to break the problem down into individual science questions
- Ignition is a "grand challenge" problem, but the experiments are integrated

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# Questions??

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7. K.L. Baker, et al., Phys. Rev. Lett., **121**, 135001 (2019) (Bigfoot)
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# Further reading


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